PHOTON SCIENCE at STANFORD LINEAR ACCELERATOR CENTER

LUSI LCLS Ultrafast Science Instruments

DESIGN REVIEW REPORT	Report No. TR-391-003-16-0
The Design Review Report Shall include at a minimum: ▪ The title of the item or system; ▪ A description of the item; ▪ Design Review Report Number; ▪ The type of design review; ▪ The date of the review; ▪ The names of the presenters ▪ The names, institutions and department of the reviewers ▪ The names of all the attendees (attach sign-in sheet) ▪ Completed Design Checklist.	▪ Findings/List of Action Items – these are items that require formal action and closure in writing for the review to be approved. See SLAC Document AP-391-000-59 for LUSI Design Review Guidelines. ▪ Concerns – these are comments that require action by the design/engineering team, but a response is not required to approve the review ▪ Observations – these are general comments and require no response

TYPE OF REVIEW: Preliminary Design Review

WBS: 1.5 Diagnostics Common Optics

Title of the Review	Intensity Position Monitor Preliminary Design Review	
Presented By:	Yiping Feng, Tim Montagne	
Report Prepared By:	Scott DeBarger	**Date:** 19 Jan 2009
Reviewers/Lab :	Scott DeBarger (SLAC) Rob Duarte (LBL) Jim Peck (SLAC) Bill White (SLAC),	

Yiping FENG
yfeng@slac.stanford.edu

LUSI
Diagnostics and Common Optics

Intensity-Position Monitor PDR
Physics Requirements

Yiping Feng – LUSI Instrument Scientist
January 9, 2009

Outline

- Introduction
  - Intensity-position monitor (IPM)
    - Primary function
    - Secondary function
- Physics Requirements
  - Performance
- Device Descriptions
- Expected Performance
- Other Requirements
  - Mechanical
  - Vacuum
  - Controls
- Summary

Yiping FENG
yfeng@slac.stanford.edu

Introduction

- IPM Functionalities

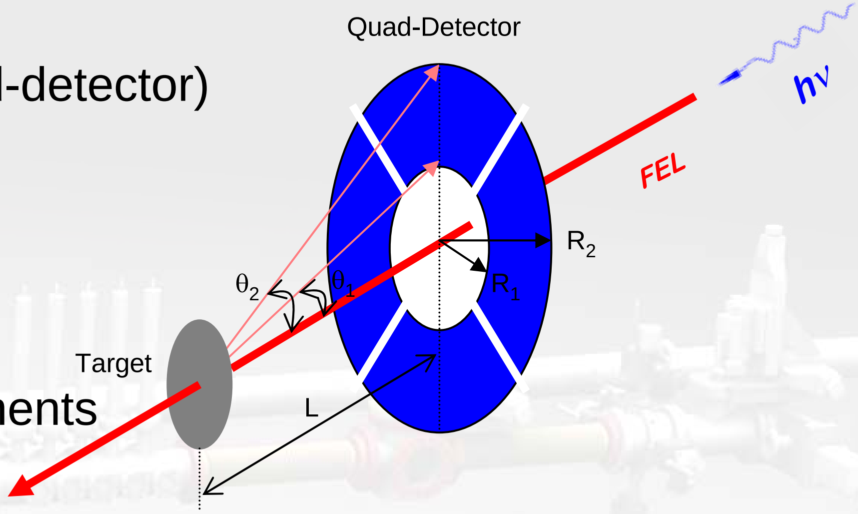
  Intensity-position monitor will be the primary diagnostic tool for X-ray intensity and position measurements

  - Primary function
    - Precise measurement of incident X-ray beam intensity
      - Intrinsic LCLS FEL intensity jitter at 30%
      - Precise normalization is critical for experiments where signal from underlying physics is small
  - Secondary function
    - Characterization of positional and pointing jitters
      - Intrinsic beam motion at 10% of beam size in both transverse directions
      - intrinsic pointing jitter at 10% of beam divergence, which can translate into large position motions at large distances (NEH @ 200 m & FEH @ 400 m)

Yiping FENG
yfeng@slac.stanford.edu

Device Concept

- Intensity-position monitor (IPM)
  - Intensity/position measurement of a FEL beam
    - System components
      - Scattering foil (target)
      - X-ray sensitive diodes (quad-detector)
      - Readout electronics
        - Charge sensitive amplifier
        - Shaping amplifier
        - Analog-to-digital converter
      - Mechanical/vacuum components
    - Operational principle
      - X-ray back-scattering from thin foil
      - Quad detectors for intensity/position measurements



Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Performance
  - **Intensity measurement of X-ray beam**
    - 0.1% relative accuracy or permitted by Poisson statistics
  - **Position measurement in X-Y plane**
    - 5 μm precision in X and Y directions
    - 5/L μrad pointing precision in X and Y directions using two monitors separated by L meters

---

- Parameters for main beam
  - FEL only
    - *2 mJ/pulse or 1.5×10^{12} photon/pulse @ 8.265 keV*
  - Unfocused beam
    - *221 μm FWHM @ 8.265 keV in NEH-3*
    - *490 μm FWHM @ 8.265 keV in FEH-5*
  - Focused beam but sufficiently far away from focus
    - Beam size still in 100 μm range
- Mono, spontaneous, 3rd harmonic or combination of them

Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

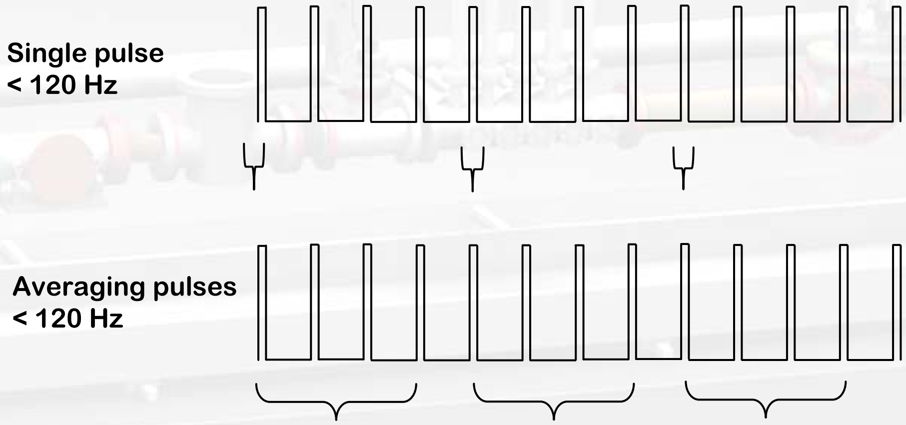
- Performance (cont'd)
  - **Operating energy 2 - 25 keV**
    - For XPP and XCS instruments
      - 4 to 8.265 keV and 3rd harmonic up to 25 keV
    - For CXI instrument
      - 2 to 8.265 keV and 3rd harmonic up to 12 keV
  - **Being highly transmissive**
    - >= 95% between 2 to 25 keV
      - 5% is the maximum signal any detection device can pick off

Incident intensity	5% pick-off	Poisson limit
1×10^{12}	5×10^{10}	0.00045%
1×10^{10}	5×10^{8}	0.0045%
1×10^{8}	5×10^{6}	0.045%
1×10^{6}	5×10^{4}	0.45% > 0.1%

Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Performance (cont'd)
  - **Capable of per-pulse operation**
    - up to max. LCLS rep. rate of 120 Hz
    - Fluctuations happens on per-pulse basis
      - Single-shot performance is required
      - If were to sub-sample, is desirable to be able to, via readout electronics,
        - Take single shot images at lower repetition rate, such as 30 Hz
        - Or sum up multiple shots at lower repletion rate, such as 30 Hz



Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Performance (cont'd)
  - **(Sensor) being able to withstand LCLS full flux**
    - unfocused full beam
    - or in a focusing geometry to a 50 μm (FWHM) Gaussian spot, but not for energies below 4 keV in NEH

- Peak fluence of unfocused beam
  - 2 mJ/pulse for fully saturated FEL

Parameters	At source	NEH-3	NEH-3 - focused	FEH-4	FEH-5
8.265 keV					
Distance from Source (m)	0	193	193	419.2	440
Beam Waist (μm)	51	188	42	396	416
Peak Fluence (J/cm^2)		3.60	70.5	0.81	0.74

Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Performance (cont'd)
  - **Minimizing wavefront distortion to the extent possible**
    - Sensor surfaces should be highly polished
      - RMS roughness ~ 10 nm ➔ +/-1% intensity variation
  - **Working range**
    - Sensor size no less than10x10 mm^2
      - large working area to accommodate beam steering by other X-ray optics
      - requiring calibration of device response function for intensity and position measurements

Yiping FENG
yfeng@slac.stanford.edu

Summary

- Performance Requirements
  - Measuring intensity of X-ray beam
    - 0.1% relative accuracy or permitted by Poisson statistics
  - Measuring positions in X-Y plane
    - 5 μm in X and Y directions
  - Operating energy 2-25 keV
  - 95% transmission for energies between 2 and 25 keV
  - Capable of per-pulse operation
  - Being able to withstand LCLS full flux
    - Unfocused
    - Slightly focused but > 50 μm (FWHM)
  - Minimizing wavefront distortion to the extent possible
  - Working area
    - 10x10 mm^2

Yiping FENG
yfeng@slac.stanford.edu

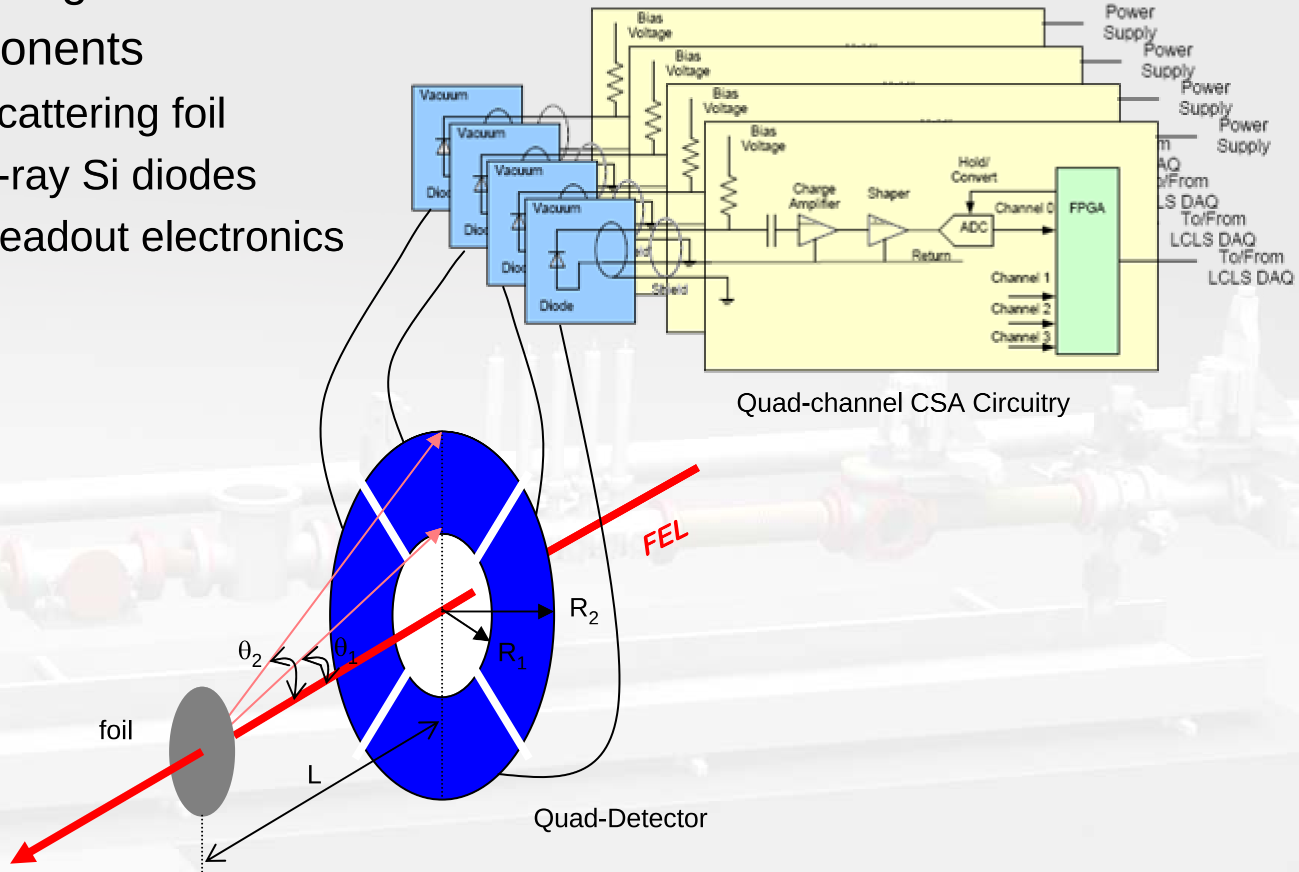
Device Concept

- Technical choices
  - Solid detector w/ high transmission
    - Capable of much larger signal while maintaining transmission requirement
      - 300 μm of Be, still 95% transmission @ 8.3 keV
      - In particular, when detecting back scattering signal from Be foil, and @8.3 keV, 0.85% total signal
      - Suitable for fully saturated FEL, mono beam, 3rd harmonic,
      - but for spontaneous, accuracy requirement not met
    - Compact size
    - Easier to implement and integrate w/ instruments

Yiping FENG
yfeng@slac.stanford.edu

Device Concept

- Conceptual Geometry
  - Detection of back scattered of X-rays
    - Scattering foil surface normal to incident FEL
    - Components
      - Scattering foil
      - X-ray Si diodes
      - Readout electronics



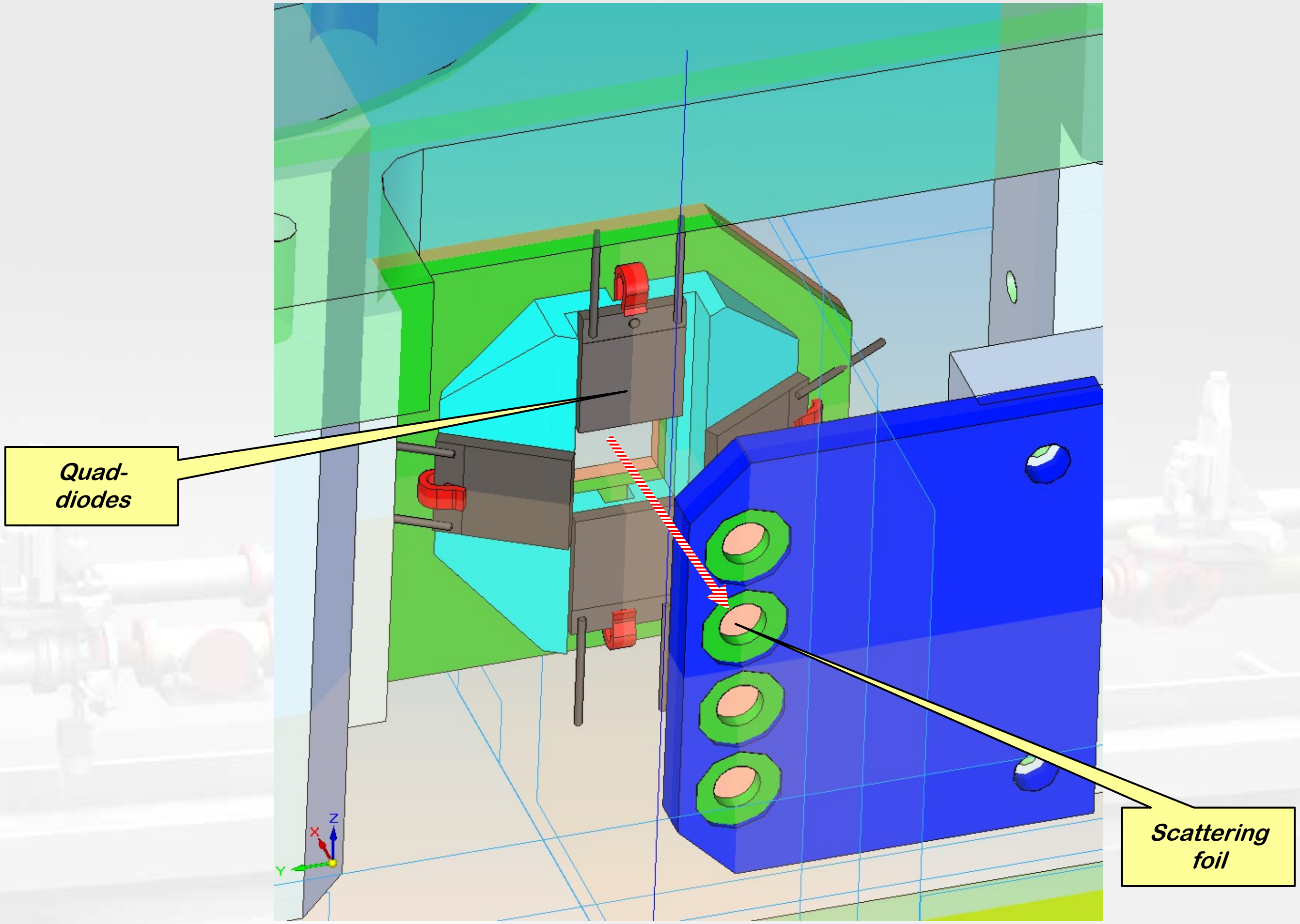
Quad-channel CSA Circuitry

Quad-Detector

Yiping FENG
yfeng@slac.stanford.edu

Device Concept

- Mechanical model (Tim's presentation)



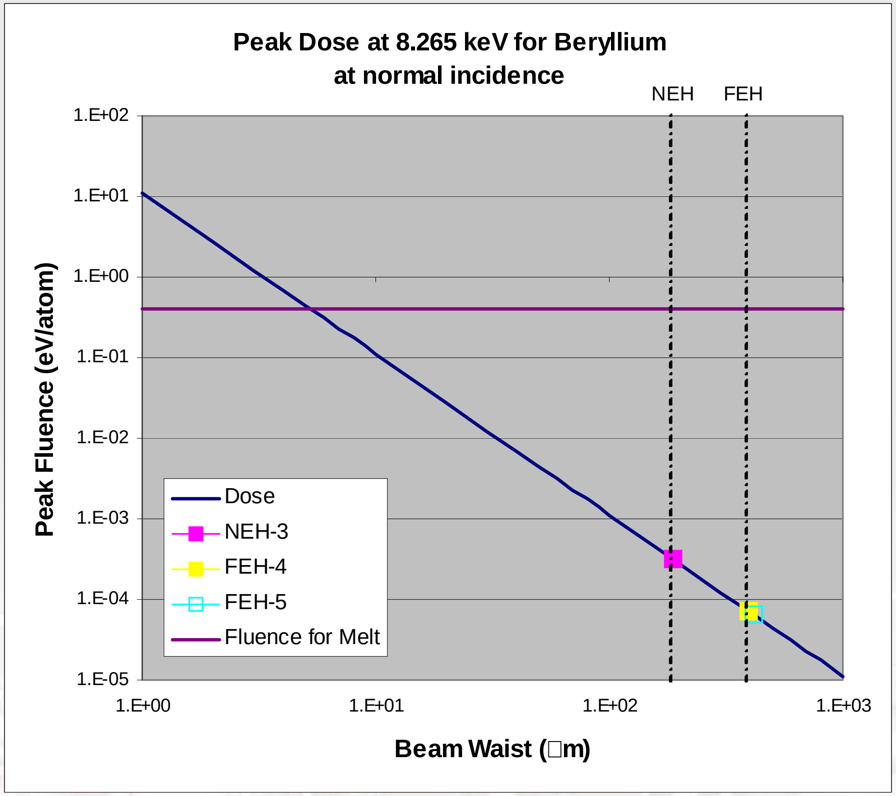
Yiping FENG
yfeng@slac.stanford.edu

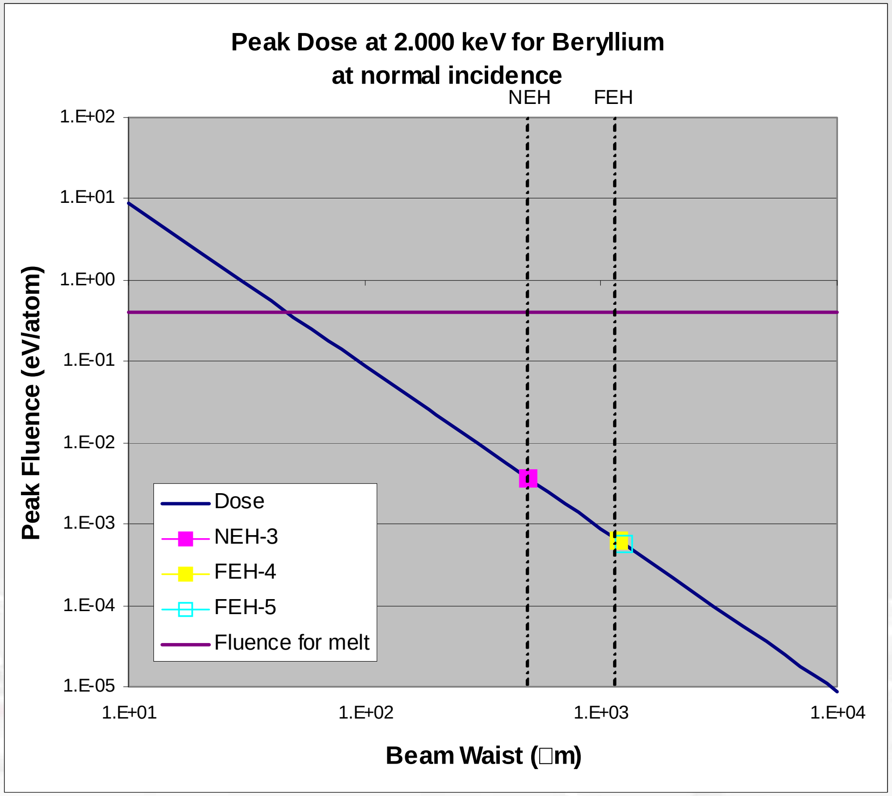
Components

- Scattering foil specifications
  - Ability to withstand the peak fluence of an unfocused X-ray FEL beam.
  - Highly transmissive in the operating range of 2 keV to 8.3 keV (w/ 3rd harmonic from 6 to 25 keV).
  - High Compton scattering cross-section to enhance back scattering.
  - Low photoelectric cross-section, but high scattering cross-section.
  - Availability in thin free-standing foil form with sufficient mechanical rigidity.
  - High density uniformity and small surface roughness so it will not become a phase object and relatively free of absorption edges.
  - Preferably in amorphous state

Yiping FENG
yfeng@slac.stanford.edu

Beryllium





$$\varepsilon = \frac{F}{L_{pe} n} = \frac{h\nu I_0 \Delta T}{\left(\frac{\pi \omega_0^2}{2}\right)} \Big/ L_{pe} n = \frac{E_{pulse}}{\left(\frac{\pi \omega_0^2}{2}\right)} \Big/ L_{pe} n = \frac{E_{pulse}}{\left(\frac{\pi \omega_0^2}{2}\right)} \sigma_{pe}$$

- Assuming 2 mJ/pulse for all energies
- Gaussian beam, w_0 is waist at z
- Source point at 1 Rayleigh length upstream of down stream end of undulator

Yiping FENG
yfeng@slac.stanford.edu

Components

- Detector specifications
  - Linear response
    - Good dynamic range
      - $I_{Input} < 10^8$ photons/pulse
  - Low dark current and readout noise
    - Each element has large area, thus needing small leakage current
  - Good quantum efficiency
    - Usable in low intensity cases
      - Spontaneous, or mono, or 3rd harmonic
      - QE > 10%
  - Low bias voltage preferred
    - Less than 500 Volts
- Large detection area
  - For measuring diffuse scattering
    - 4 10x10 mm^2
- Vacuum compatible
  - Operable as part of instrument
  - Solid state, not gas based
    - No differential pumping

Yiping FENG
yfeng@slac.stanford.edu

Components

- Si diodes
  - Internal photoelectric
    - Low e-h generation energy
      - 3.62 eV => 1 e-h pair
    - Low carrier density in depletion region
      - Low dark current if detection area if small
    - Reasonable bias voltage
      - Low dark current
    - Internal gain
      - 2300 e-h pairs per 8.265 keV X-ray photon via initial fast photoelectron & subsequent cascading processes
    - High quantum efficiency
      - 93% @ 200 μm @ 8.267 keV
  - High damage threshold
    - w/ moderate attenuation, capable of sustain FEL at normal incidence

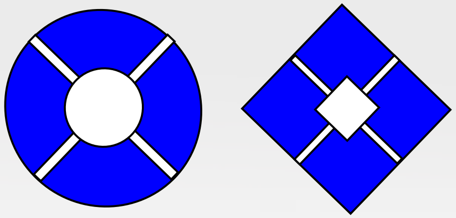
- Si diodes (cont'd)
  - Readily available
  - Vacuum compatible

Si Diode/PIN diode	
e-h pair generation	3.62 eV
Quantum efficiency	93% @ 200 μm @ 8.267 keV
Dark current	~ 1 nA/mm^2 @ 100 V
Dark charge when intergrated	~ 0.1 fC/mm^2 @ 100 ns
Bias (reverse) voltage - Fully depleted	100 – 300 V

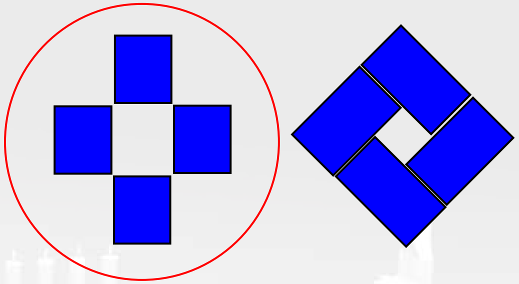
Si Diodes

- Array diodes

•Monolithic design
•Expensive fabrication
•High collection efficiency



•Four-diode design
•Readily available/easy assembly
•Less collection efficiency/difficult to model

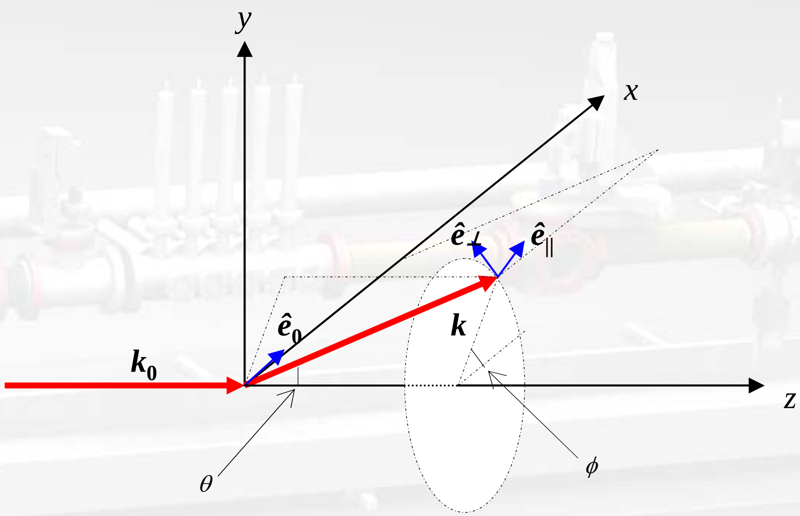


- Possible choices
  - Having sufficient depletion thickness for high QE
    - IRD international
    - Canberra PIPS
    - Hamamatsu
    - UDT sensors (used by Oxford Danfysik QBPM)

Yiping FENG
yfeng@slac.stanford.edu

Scattering Processes

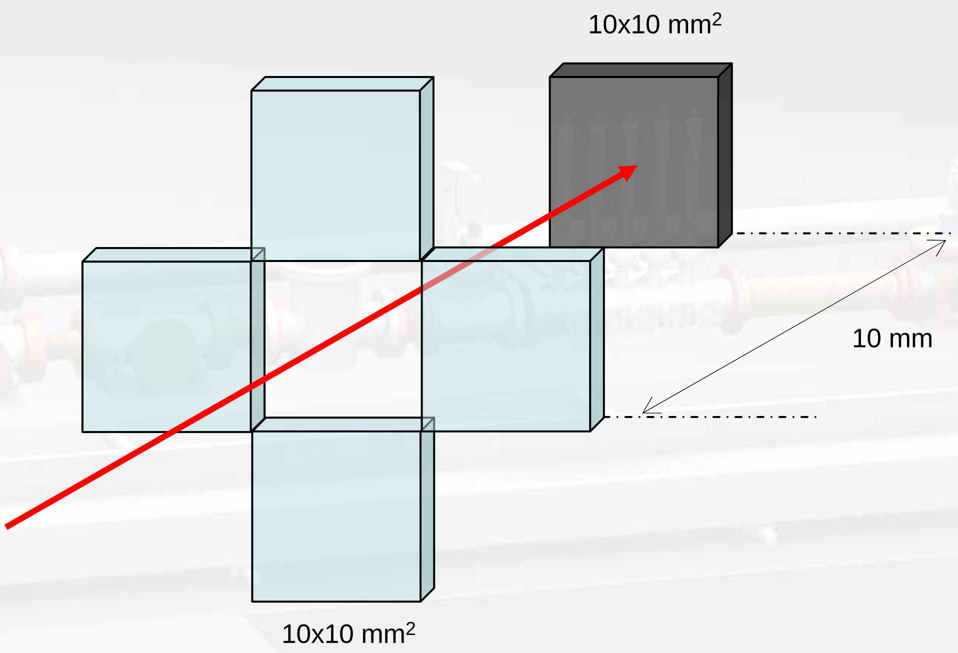
- Scattering signals
  - Compton scattering
    - Higher cross-section in back scattering geometry
    - The lower the Z, the higher the cross-section
  - Thomson scattering
    - Mostly in the forward direction
    - Proportional to Z^2
  - K-fluorescence
    - Negligible at low Z
  - Photoelectrons
    - Primary electrons
    - Auger electrons



Yiping FENG
yfeng@slac.stanford.edu

Simulations

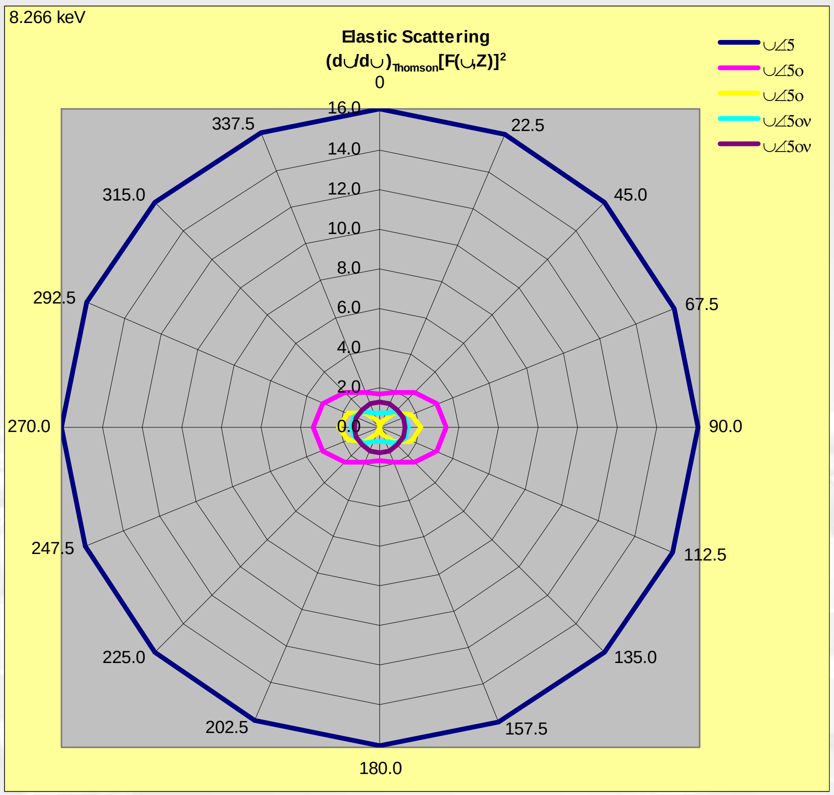
- Simulation parameters
  - 10x10 mm^2 Beryllium
  - Scattering geometry
  - 4 10x10 mm^2 silicon diodes

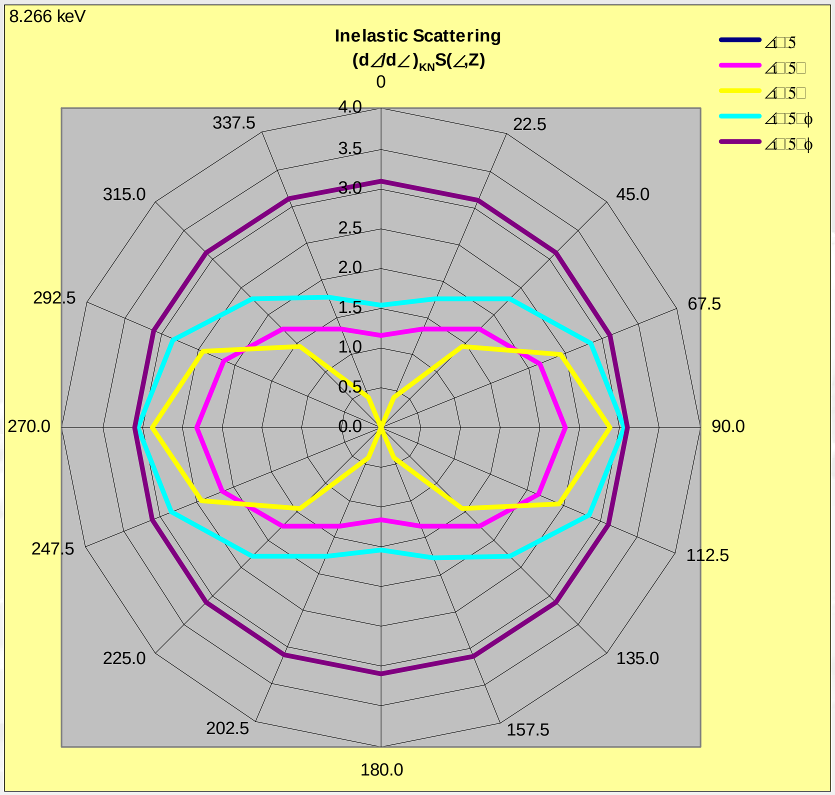


Yiping FENG
yfeng@slac.stanford.edu

Scattering Pattern

- Back scattering cross-sections
  - Inelastic & elastic
    - Highly anisotropic





Yiping FENG
yfeng@slac.stanford.edu

Simulations

- Expected signals
  - Multiple thickness needed for optimal signal

Parameters			1st order	1st order w/ mono @ 2%	3rd order @ 1%	3rd order w/ mono @ 2%
1st order @ 8.265 keV, 3rd order @ 24.797 keV	Incident (photons/pulse)	FEL	1.50E+12	3.00E+10	1.50E+10	3.00E+08
		spontaneous only @ 10^{-4}	1.50E+08	3.00E+06	1.50E+06	3.00E+04
	Beryllium foil thickness (□m)		297		1622	
	Scattered (photons/pulse)	w/ FEL	3.27E+09	6.55E+07	1.38E+08	2.76E+06
			0.002%	0.012%	0.009%	0.060%
	Scattered (photons/pulse)	w/ Spontaneous	3.27E+05	6.55E+03	1.38E+04	2.76E+02
			0.17%	1.24%	0.85%	6.02%
1st order @ 2.000keV, 3rd order @ 6.000 keV	Incident (photons/pulse)	FEL	6.20E+12	1.24E+11	6.20E+10	1.24E+09
		spontaneous only @ 10^{-4}	6.20E+08	1.24E+07	6.20E+06	1.24E+05
	Beryllium foil thickness (□m)		25		115	
	Scattered (photons/pulse)	w/ FEL	1.72E+09	3.45E+07	5.78E+07	1.16E+06
			0.0024%	0.0170%	0.0132%	0.0930%
	Scattered (photons/pulse)	w/ Spontaneous	1.72E+05	1.72E+05	1.72E+05	1.72E+05
			0.24%	1.70%	1.32%	9.30%

Yiping FENG
yfeng@slac.stanford.edu

Simulations

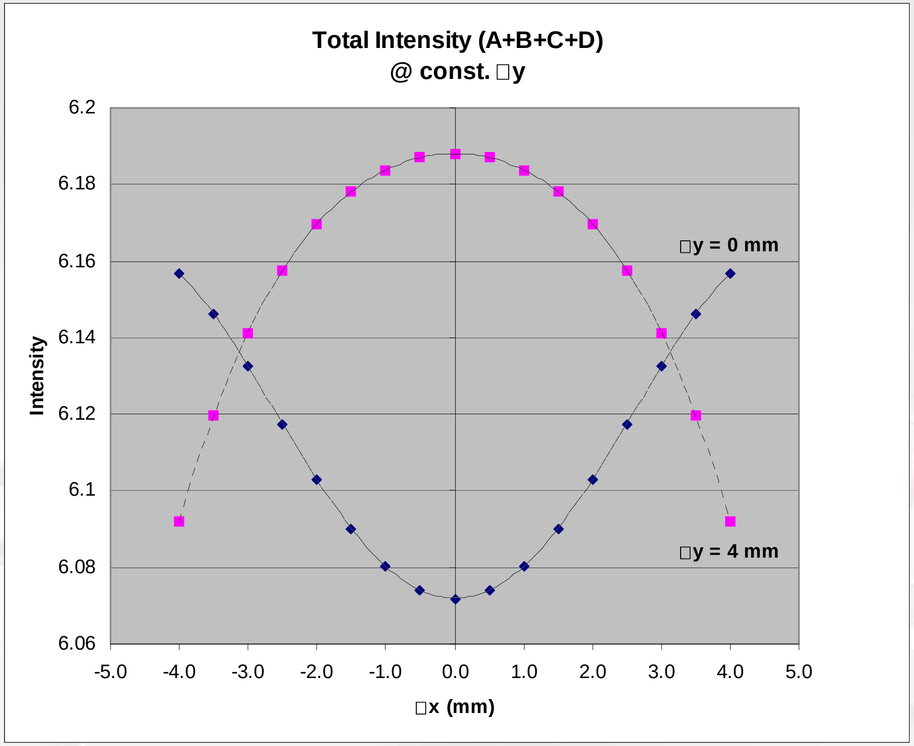
- Expected performance for the diodes
  - Driving readout electronics (controls' review)

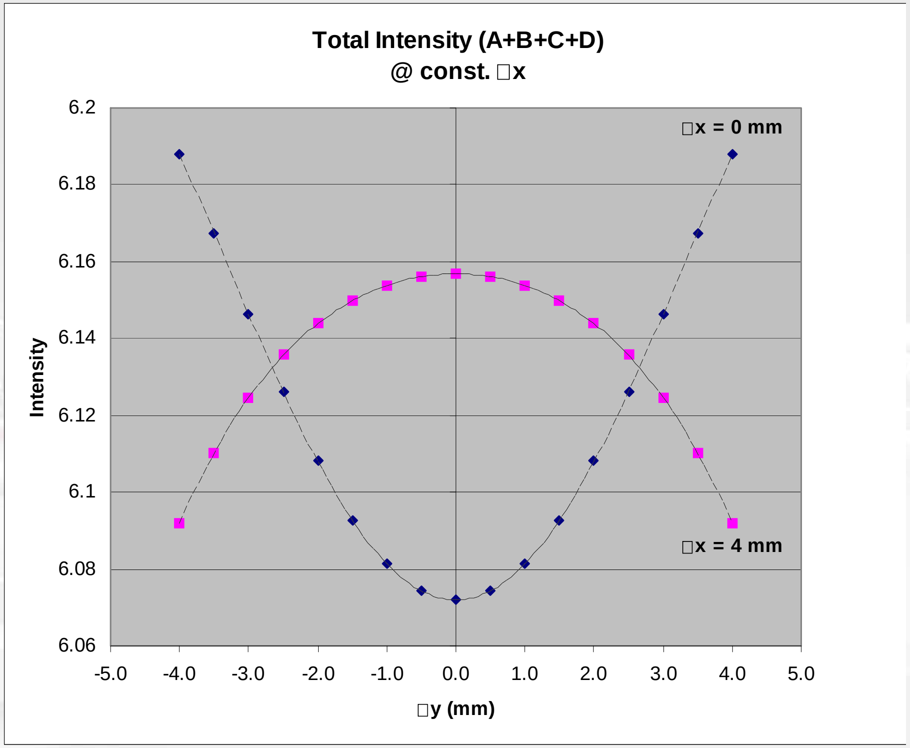
	quad diodes	
	high limit	low limit
size (mm^2)	100	
depletion thickness (μm)	500	
device effective capacitance (w/ bias) (pF)	21.1	
incident intensity (γ/pulse)	$1.5x10^{12}$	
Attenuation factor or scattering efficiency	$2.5x10^{-5}$	
intensity on diode (γ/pulse)	$3.8x10^7$	$3.8x10^5$
e-h pairs generated (#)	$8.5x10^{10}$	$8.5x10^8$
equivalent amount of charge (nC)	$1.4x10^1$	0.14
OpAmp feedback capacitance (pF)	10000	1000
output voltage (mV)	1369	136.912
Poisson limited accuracy for sum signal	0.01%	0.08%

Yiping FENG
yfeng@slac.stanford.edu

Intensity Measurement

- Response function
  - Total signal not constant if beam center moves
    - ~ 1.5%/4000 μm

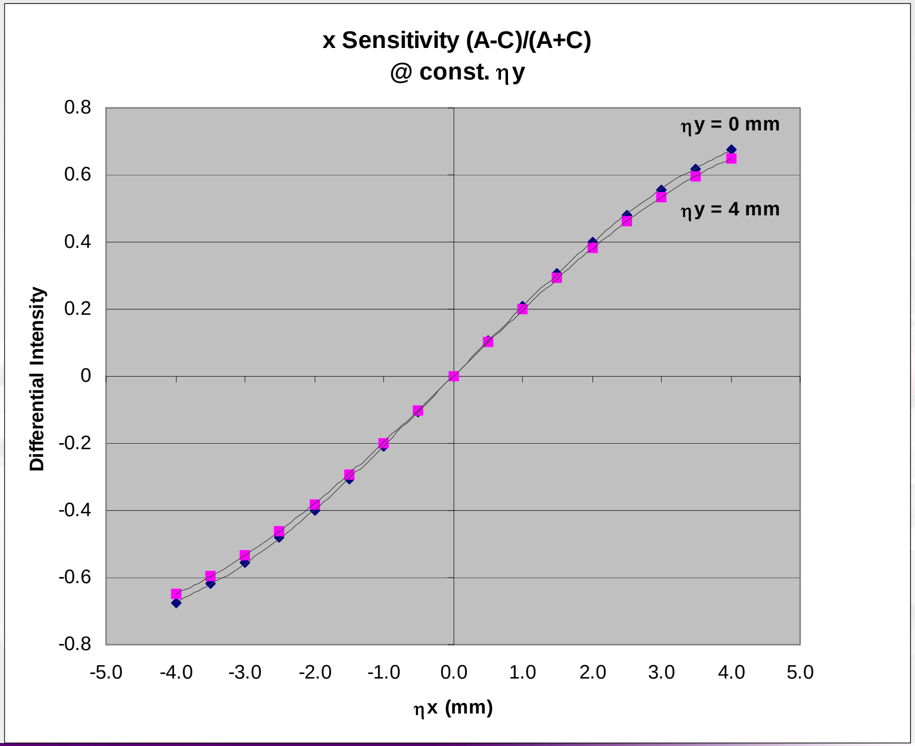


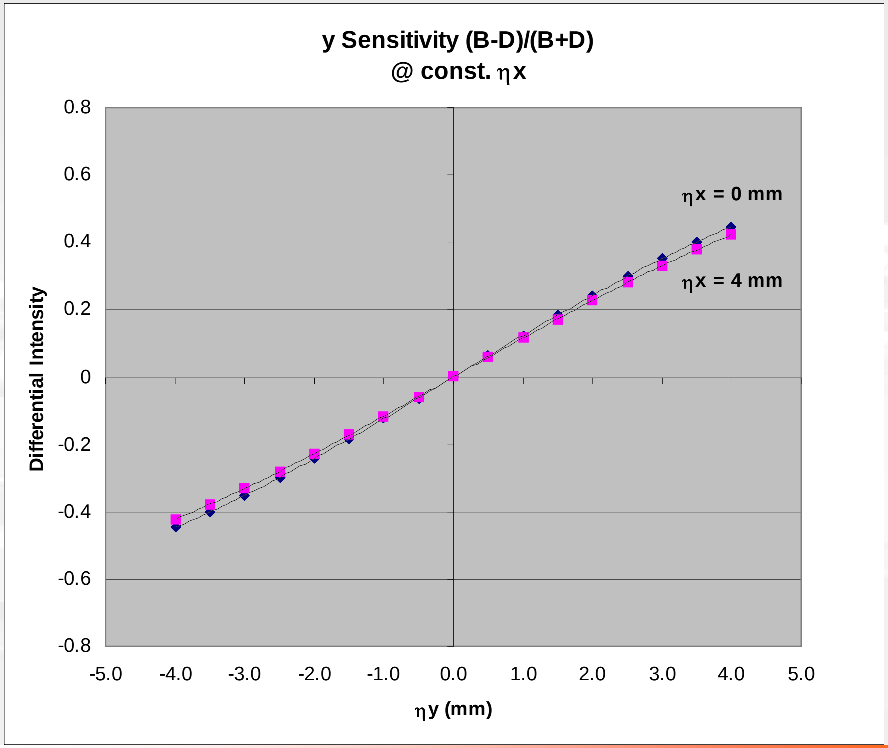


Yiping FENG
yfeng@slac.stanford.edu

Position Measurement

- Response function
  - Almost linear
    - Max deviation ~ 20% in x-direction ➔ calibration required
  - Position resolution $\Delta x = \eta \frac{\sqrt{I}}{I} L \Rightarrow 6-8\mu m$

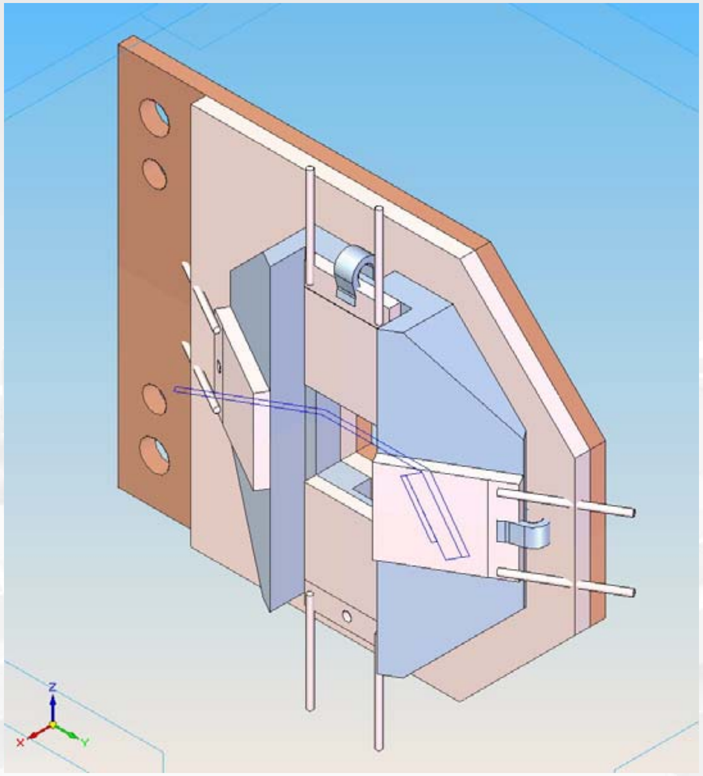


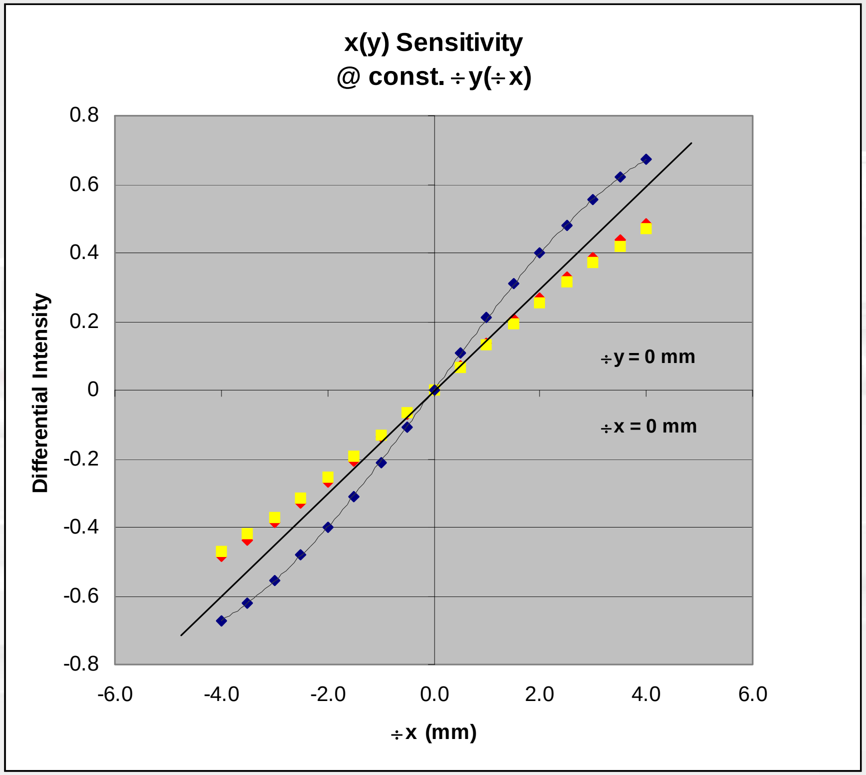


Yiping FENG
yfeng@slac.stanford.edu

improvement

- Detector rotation
  - In y-direction only (see model and Tim presentation)
    - X sensitivity ~ Y sensitivity
    - Improved max. deviation to 10%

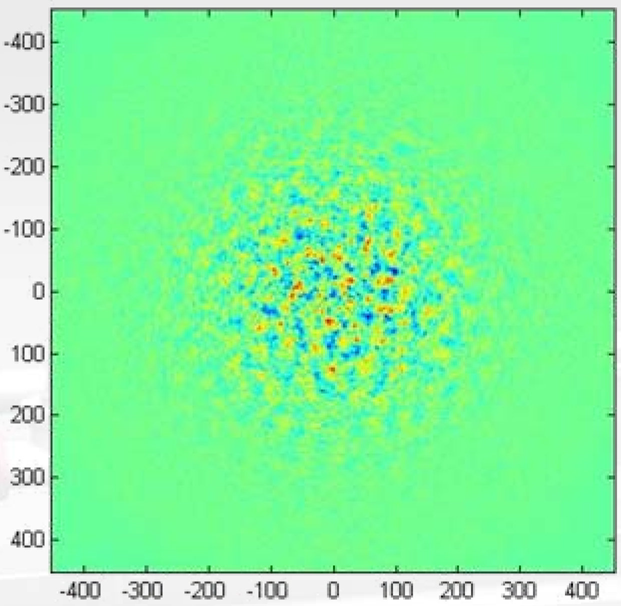


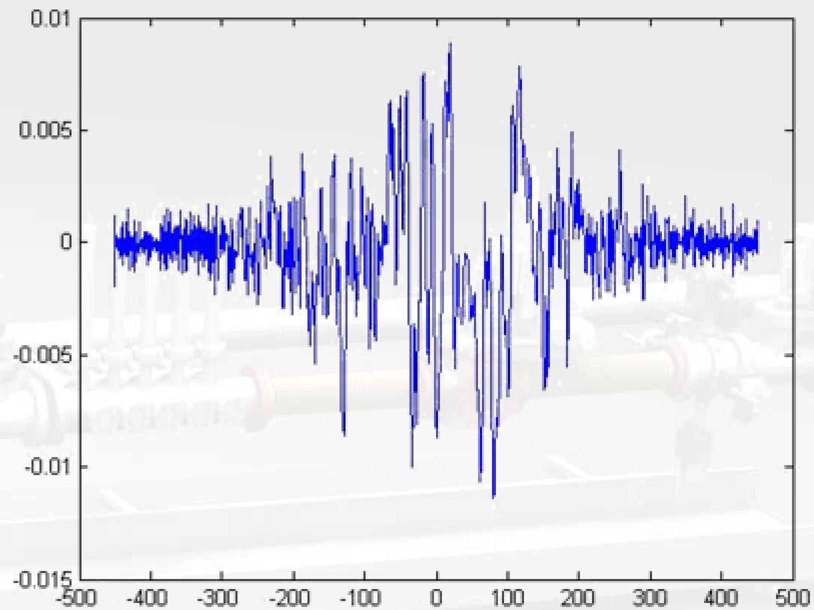


Yiping FENG
yfeng@slac.stanford.edu

Wavefront Distortion

- Coherent wavefront propagation
  - Generated surface morphology
    - Based experimental power-spectrum density (PSD)
  - 10 nm rms roughness





Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Mechanical
  - **Operating positions (states)**
    - "In" position – partially transmissive to beam
    - "Out" position – retracted if needed
  - **Maximum time to change states**
    - 30 seconds from "Out" to "In" or vise versa
  - **Surveyed-in "In" position of sensor**
    - To 5% of sensor working area of 10x10 mm^2
      - 500 μm in X and Y directions
    - Desirable to align surface normal of sensor to ±1º of Z-axis or nominal FEL beam propagation axis
      - To be further discussed below

Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Mechanical (cont'd)
  - **<u>Accuracy, resolution, and repeatability in X-Y plane</u>**
    - 5 μm in X and Y directions
  - **<u>Stay-clear</u>**
    - When in "Out" position, should be1/2" from nominal FEL propagation axis
  - **<u>Compatibility to instruments</u>**
    - Consistent w/ XPP, CXI, XCS instruments
  - **<u>Repairs</u>**
    - Sensor should be field replaceable

Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Vacuum
  - **Vacuum compatibility**
    - High vacuum @ 10^{-7} torr
- Controls
  - **Remote operation**
    - State change
    - X and Y positions
    - Start/stop intensity measurement
  - **Intensity measurement at machine repetition rate**
    - Per-pulse operation up to max. LCLS rep. rate of 120 Hz

Yiping FENG
yfeng@slac.stanford.edu

Physics Requirements

- Controls (cont'd)
  - **Online data processing**
    - X and Y positions calculations
    - Running averages
    - Standard deviations
    - Histogram display, etc.
  - **Archiving**
    - Capable of saving raw data, and processed data
  - **Local equipment protection implementation**
    - Providing interlock logics for safe operation to avoid beam damages
      - Pulse picker or attenuator

Yiping FENG
yfeng@slac.stanford.edu

PHOTON SCIENCE at STANFORD LINEAR ACCELERATOR CENTER

LUSI LCLS Ultrafast Science Instruments

DESIGN REVIEW REPORT	Report No. TR-391-003-16-0

The Design Review Report Shall include at a minimum:

- The title of the item or system;
- A description of the item;
- Design Review Report Number;
- The type of design review;
- The date of the review;
- The names of the presenters
- The names, institutions and department of the reviewers
- The names of all the attendees (attach sign-in sheet)
- Completed Design Checklist.
- Findings/List of Action Items – these are items that require formal action and closure in writing for the review to be approved. See SLAC Document AP-391-000-59 for LUSI Design Review Guidelines.
- Concerns – these are comments that require action by the design/engineering team, but a response is not required to approve the review
- Observations – these are general comments and require no response

TYPE OF REVIEW: Preliminary Design Review

WBS: 1.5 Diagnostics Common Optics

Title of the Review	Intensity Position Monitor Preliminary Design Review	
Presented By:	Yiping Feng, Tim Montagne	
Report Prepared By:	Scott DeBarger	**Date:** 19 Jan 2009
Reviewers/Lab :	Scott DeBarger (SLAC) Rob Duarte (LBL) Jim Peck (SLAC) Bill White (SLAC),	
Distribution:		
Attachments:	☐ Review Slides ☐ Design Checklist ☐ Calculations ☐ Other	

Purpose/Goal of the Review:

- Assess the completeness of physics and engineering requirements for the Intensity Position Monitor.
- Review the preliminary design of the Intensity Position Monitor and evaluate how well it meets the requirements
- Review the interfaces that have been identified and how well they have been communicated to the relevant parties (includes controls and software interfaces, safety review committees, instrument design teams)
- Assess plans for fabrication, assembly, testing and inspection, and maintenance
- Review the cost estimate and schedule.
- Identify high-risk elements and evaluate plans to mitigate the risk.

Comment on whether the component design is ready to proceed to final design

Introduction and outcome summary of the review:
The presented design for the Intensity Position Monitor appears to satisfy the stated need to measure X-ray beam intensity and position to a high level of precision over a large of incident beam intensities.

The mechanical design is economical in its use of space while permitting appropriate *in situ* disassembly for servicing of in-vacuum components.

The review committee feels that the presented preliminary design is sound and should be advanced to the Final Design Review level.

Findings/Action Items:
Exact conductor counts and connector styles for the vacuum feedthroughs were not specified. This needs to be done before the feedthroughs are procured.

Concerns:
The presented detector array was shown, in simulations, to accurately measure to variations in beam position in X or Y. It is unclear that the same is true of variations at an arbitrary angle. A study of response to beam motion at a 45 degree angle should be performed.

Observations:
<u>General</u>
The presented specification calls for wavefront distortion to be minimized “to the extent possible.” Quantifying the allowable wavefront distortion based on the operational requirements of the device will permit the design team to ascertain their success in meeting this requirement.

The foil material will subjected to cyclic thermal loading as each light pulse strikes the foil. Fatigue of the foil material over the anticipated life of the instrument should be investigated.

The details of the manner in which the Be screen will be held need to be developed.

The device has been designed to be economical of beamline space and to permit installation in multiple locations. The specific installation locations should be checked to ensure that bolts can be loaded into the vacuum flanges for the specific combination of devices at that location.

The Intensity Position Monitor is expected to be installed in locations where there are additional beamlines in close proximity to the installed device. If components from these beamlines are close in X to the Intensity Position Monitor, access for service of the in-vacuum components may be compromised.

The difficulty of removal of the diode actuator will affect operations to service the diode. As presented the diode actuator is offset from the path of the photons through the instrument. Moving the diode actuator onto the photon path may ease removal of the actuator. Removal of the entire top of the vacuum chamber may also be a design option worth exploring.

A general plan for prototyping and testing was presented. Consideration should be given to adding tests of the first articles with the LCLS photon beam (possibly in the FEE, Hutch 3, or XTOD areas).

Procurement of beryllium material for the scattering foil may be a long lead item. Procurement of the material should be pursued aggressively.

Response to Findings/Action Items:

Exact conductor counts and connector styles for the vacuum feedthroughs were not specified. This needs to be done before the feedthroughs are procured.
Response: Based on conversations with the controls group, a standard 16 pin D connector will be used for the vacuum feedtrhoughs. This will be sufficient for all the signal and grounding signals.